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Parameterization of daily solar irradiance variability

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ABSTRACT

The effects of solar systems operation can be compared only under very similar weather conditions. Diagnostics of the solar systems requires unequivocal determination of solar irradiation. Development of a method for precise identification of solar radiation day time profile is needed, as the methods used so far in the cloud cover determination are not satisfactory. The paper presents two optional methods, developed by the authors, for identification of the solar radiation profile. Advantages and disadvantages of the methods are also specified.

Contents

1. Introduction

Accurate assessment of daily operational efficiency of the solar thermal heating and photovoltaic (PV) systems calls for unequivocal determination of a curve that characterize distribution of the daily sun radiation. This curve is also needed for comparative analysis of many other thermal systems.

Previous studies on similar problems have been concentrated on the summary daily sun radiation and sometimes on cloudiness degree as the key factors to determine operational efficiency of the examined solar systems. Thermal efficiency is assumed as directly proportional to daily solar irradiation, on condition that it is greater than its threshold value (e.g. ISO 9459 [1]). To some degree it is a simplified assumption. Sun radiation intensity forces modification of its distribution curve. Irradiance variability in time determines the heat transfer dynamics. Every change in distribution curve is critically important, as it greatly affects the assessment results of solar thermal systems' operational efficiency.

Radiation variability at a given geographical location results from two overlapping phenomena: (1) parabola of sun movement on the sky is determined by a subsequent day, and (2) a stochastic course of cloudiness. If sky is clear, it is relatively easy to determine variability of total radiation intensity for the determined atmosphere turbidity [2].

Many empirical studies indicate the need for more precise identification of the radiation course, not only on the basis of average hourly values [3,4]. Assessment of daily operational efficiency of solar heating and photovoltaic systems should be based on data that characterize irradiance changeability in the short intervals (in hours and even shorter periods).

The authors of this paper propose two empirical methods for parameterization of the sun radiation variability, including description of the methods and the results of their practical application.

2. Classification of changes in solar irradiance conditions

Cloudiness of stochastic character determines the instantaneous irradiance value. In meteorology, the cloudiness is determined by firmament coverage with clouds; if clouds cover the sky totally the cloudiness is designated with 8, if the sky is totally clear then 0 is assigned. Number 9 is additionally reserved for the case when the cloud cover cannot be determined because of smog, fog, etc.

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The formulation of solar irradiance models is a complex and difficult task, particularly when obtaining of needed data of good quality is impossible. In such cases, the cloud coverage observations are used as basis information [5].

Belcher and DeGaetano [6] provided information on typical hourly cloud cover classes for the United States conditions and the use of Automated Surface Observation System (ASOS). They formulated the solar irradiance model and determined seven types of hourly cloudiness:

- clr – clear sky;
- few – few clouds on the sky;
- sct – scattered clouds;
- bkn – broken clouds (there are some clear sky breaks and big cloud groups);
- ovc – overcast;
- obs – total cloud cover;
- multi – hours of observations when at least one cloud has appeared.

The visual evaluation of cloud cover made by individual observers differed distinctly from ASOS results, particularly in clr category (almost twice more frequent hours were indicated by ASOS) and in the sct and bkn categories (over twice bigger frequency of such hours were indicated by visual observers).

The cloud cover degree and complementary clearness index K_T (the ratio of global horizontal radiation G to horizontal extraterrestrial radiation G_o) and sunshine hours are basic parameters used to formulate solar radiation models for different regions of the world. Tens of correlation models have been formulated all around the world, to examine the relationship between the ratio of mean daily global irradiation in a given month (G_{day}) and monthly average extraterrestrial radiation values ($G_{o,day}$) and the ratio of average daily hours of bright sunshine (S_{day}) and the average solar day length ($S_{o,day}$) [7]:

$$K_{T,day} = \frac{G_{day}}{G_{o,day}} = a + \frac{b \times S_{day}}{S_{o,day}}$$

The numerical values of the regression coefficients a and b differ when other independent variables including location latitude, sun declination, atmosphere temperature, etc., are used.

Development of measurement technique enabled to determine (characteristic for a given region) the classical correlation between the share of diffuse radiation D_{hor} in total radiation sum G_{hor} (diffuse ratio) on a horizontal surface and the clearness index K_T [8]:

$$\frac{D_{hor}}{G_{hor}} = f\left(\frac{G_{o,hor}}{G_{hor}}\right)$$

These correlations are needed in calculations of radiation sums on the inclined surfaces, when only total irradiation measurement is available for the horizontal surface [9]. Improvement of models of Liu–Jordan type, from one hand consists in testing of correlation in shorter and shorter time intervals [10,11], and from the other hand in introduction of additional variables like the sun height, optical mass, atmosphere humidity, etc. [12,13]. At the same time, it was observed that under the cloudless and variable cloudiness conditions, the daily and also hourly clearness indices often take the same values. It results then in poor correlation between diffuse ratio and the K_T value. A substantial improvement in model quality can be obtained by introduction of clearness variability index in hour intervals as a new parameter [14].

Parameters of solar irradiation variability are particularly useful if a model of Liu–Jordan type is to be based only on measurements of total irradiation on the horizontal surface. The scientists developing in this way a correlation model with the use of meteorological station data in Catalonia (Spain) divided every hour into twelve 5-min intervals $N = 12$, where average solar irradiation value was recorded [15]. They proposed three indexes of hourly variability for the standardized clearness index K'_T (standardization is connected to current value of optical mass). The first one is based on standard deviation of mean value $\overline{K'_T}$ of the whole hour:

$$\Delta_1 = \ln \frac{\sigma}{\overline{K'_T}}$$

where standard deviation has the form:

$$\sigma = \frac{\sqrt{\sum_{i=1}^{N}(K'_{Ti} - \overline{K'_T})^2}}{N-1}$$

The second index contains the notion of absolute deviation sum between subsequent 5-min values:

$$\Delta_2 = \ln\left(\frac{1}{(N-1)\overline{K'_T}}\sum_{i=1}^{N-1}|K'_{Ti+1} - K'_{Ti}|\right)$$

The third index takes into account the difference between extreme values in a given hour:

$$\Delta_3 = \ln\left(\frac{1}{(N-1)\overline{K'_T}}|K'_{Tmax} - K'_{Tmin}|\right)$$

Indexes of hourly variability of clearness index and its mean value were then used (in various combinations) in multi-parameter models to describe the diffuse irradiation fraction. The results in the form of linear least-squares regressions were compared to analogical dependences obtained according to the classical procedures. Statistical evaluation of the models showed higher quality of models supported with variability indices.

The cloud cover classifications have no direct connection to variation of solar irradiation levels. The researchers of solar energy systems consider the solar irradiation as an input signal for the state of system operation. Particular days are grouped on the basis of signal level and its variation in time. The methods for classification of days in regard to solar conditions are based on statistic instruments and give different results depending on climatic zones and particular purpose of classification. The classic method used for classification of days according to cloud cover is based on the analysis of clearness index histograms K_T.

For example, Maafi and Harrouni [16], who classified solar conditions in southern Algeria, used two threshold criteria in their algorithm. The first one refers to frequency distribution of global irradiance (D), and the second one to the beam clearness index). Three classes of days were introduced:

- Clear sky day: $1 \le D \le D_1$ and $K_T \ge 0.5$.
- Partially cloudy sky: $D_1 < D \le D_2$ and $K_T \ge 0.5$.
- Completely cloudy sky: $D_2 < D$ or $D \le D_2$ and $K_T < 0.5$.

A cumulative distribution function was used to determine the thresholds D_1 and D_2. In this case the classification was carried out for the need of photovoltaic power plants.

Soubdhan et al. [17], who investigated climatic conditions in the Caribbean, introduced another method for classification of days according to daily irradiation conditions. The determination of characteristic types of daily variation was related to the dynamics of energy transformation in photovoltaic systems. The basic information obtained from the analysis of annual results was the daily frequency histogram of the beam clearness index K_T in 20 fractional ranges. The identification of histogram classes and affiliation probability of particular daily histograms for the established class was

performed by statistic methods based on a finite mixture of Dirichlet distributions. As a result, the authors determined three features of daily irradiation:

- sunny (S): S = 1 – clear sky condition, S = 0 – other,
- overcast level (C): C = 0 – no cloud; C = 1, C = 2 – total cloud cover,
- dynamic level (D): D = 0, D = 1, D = 2 – relates to the velocity of clouds and their size.

The analysis of these feature combinations led to the identification of four classes for daily irradiation:

(a) First class – for S = 1, C = 0 and D = 0. This class is represented by a clear sky with low number of clouds. The most frequent are periods of $K_T = 0.75$. In the climate of Guadalupe 7% of days were affiliated.
(b) Second class – for S = 1, C = 1, D = 1. This class is represented by days of high solar irradiance but interrupted with medium size clouds of limited velocity.
(c) Third class – for S = 0, C = 2, D = 0. This class is represented by cloudy days, i.e., the sky is covered with big multilayer clouds of low velocity. The frequency of K_T is highest when it ranges between 0.1 and 0.2.
(d) Fourth class – for S = 1, C = 2, D = 2. This class is represented by days of sun only periodically covered with small clouds. The index frequency K_T reaches two peaks – for 0.25 and 0.75. This class predominates in this climate for 52% days in a year.

The classification analyses of daily irradiance waveform are carried out to distinguish days of somehow similar features within the whole population of days. The methods and classification criteria assume a limited number of classes; as a result, days of different irradiance variation are included in the same class.

A method for classification of days according to short-term variability in solar irradiation under conditions of North Europe climate was presented by the Estonian scientists [18]. The database included a period from April to September of 1999–2002 (detailed analyses concerned the May–July period). Ten hours that were symmetrically situated around the solar noon were considered. The measuring sequences subjected to analysis consisted of 1-min values of total radiation G. A 10-min interval was taken as the basic interval for investigation on irradiation stability. The following index of radiation intensity variability for 60 subsequent intervals was proposed:

$$\sum_{i=1}^{10} |G_{i+1} - G_i|$$

If this index value exceeded 1000 W/(m^2 min), the interval was qualified as unstable. It was assumed that if the unstable interval sum exceeded 5 h (half of the day), this day was arbitrarily counted to a highly unstable group. However, if the unstable interval sum was equal to less than 1 h, this day was conventionally regarded as stable one. In summer months under Estonia climate the cloudless stable days amounted to 10.7% of the entire analyzed period and they supplied 16.7% of total energy. Days of strong cloud cover, that were also qualified as stable ones, made 8.8% of the period and supplied 2.7% of total energy. At the next stage of investigations there was developed methodology for evaluation of irradiation conditions variability that eliminated the notion of basic N-minute interval. Differences ΔG between radiation intensity values in the subsequent minutes of the day were presented in the form of distribution curve. The curve shape was characteristic for variability of solar irradiation conditions. Periods of gradients $\Delta G < 50$ W/(m^2 min) predominate on the cloudless days. On the average, 16.2% of such days' length were characterized by ΔG gradient equal to zero. However, days of variable cloud cover were not univocally parameterized.

For research purposes, the irradiance waveform is related to 1 h or sometimes to even shorter period, e.g. to 1 min. It can be found in investigations on the effect of short-term irradiance and its components in classical methods of calculations of global radiation on differently exposed surfaces. Short-term solar conditions vary mainly as a result of cloud movement and that is why diffuse component analysis is so important. It appears that the use of short-term data, compared to hourly averages, does not affect the results of monthly global radiation. However, if a useful solar fraction is determined, i.e. the one exceeding the established threshold (utilizability concept), the range of averaging basic measurement data greatly influences the shape of determined waveforms. The utilizability based on 3-min averaging is by 10–30% higher for critical values ranging from 200 to 500 W/m^2, when compared to 1-h averaging [19]. Within the remaining critical value ranges these differences are not so big. Simulations of solar energy conversion efficiency in power systems based on short-term radiation data should also lead to correction of the results based on hourly averages.

3. Methodology

In simulation computations for solar system heating efficiency and testing of real systems the hourly average irradiation is used as a standard. The comparison of efficiency and dynamics of heating solar systems within the energy diagnostics requires definite evaluation of radiation conditions during tests. It is advised to introduce a parameter (an indicator) to identify the days of different cloud covers in the same group of daily global irradiation. The effects of heating solar system operation depend not only on daily dose but also on its waveform during a day. The authors introduce a concept of daily parameterization for solar irradiance and present two different methods to determine the variation parameter without any preference. Both of them have their advantages and disadvantages, and in each of the methods a particular day is definitely described by means of rational indexes, however, sometimes of different values.

The first method uses an elementary index of property variation as a standard deviation σ related to the mean value (variation indicator Wz). The investigated property is global solar irradiance G recorded at minute intervals. Solar days in this method are divided into equal time intervals $\Delta\tau$ of k-minutes. The number of intervals n results from the number of m minutes from sunrise to sunset:

$$n = \frac{m}{k} \tag{1}$$

Range variation indices are determined for particular day:

$$(W_z)_{\Delta\tau} = \sigma_{\Delta\tau}\bar{G}_{\Delta\tau} \tag{2}$$

where $\Delta\bar{G}_{\Delta\tau}$ is average irradiance in a time interval, W/m^2.

Variation index for the whole day $(Wz)_d$ is weighted average of time intervals' values related to arithmetic mean irradiance for the whole day. The weight is the share of irradiation from i-interval in the daily sum H that is expressed in this paper in Wh/m^2:

$$(Wz)_d = \left(\frac{\left(\sum_{i=1}^{n} \sigma_{\Delta\tau_i} G_{\Delta\tau_i} k\right)/60H}{60H/m} \right) \tag{3}$$

Introduction of weight for intervals' values aimed at intensification of variation rank of radiation conditions in the periods of highest radiation intensity. This method is thus useful for precise determination of solar conditions for heating systems, where the periods of low radiation are not important. The value of $(Wz)_d$ is strongly influenced by the accepted daily number of intervals. The

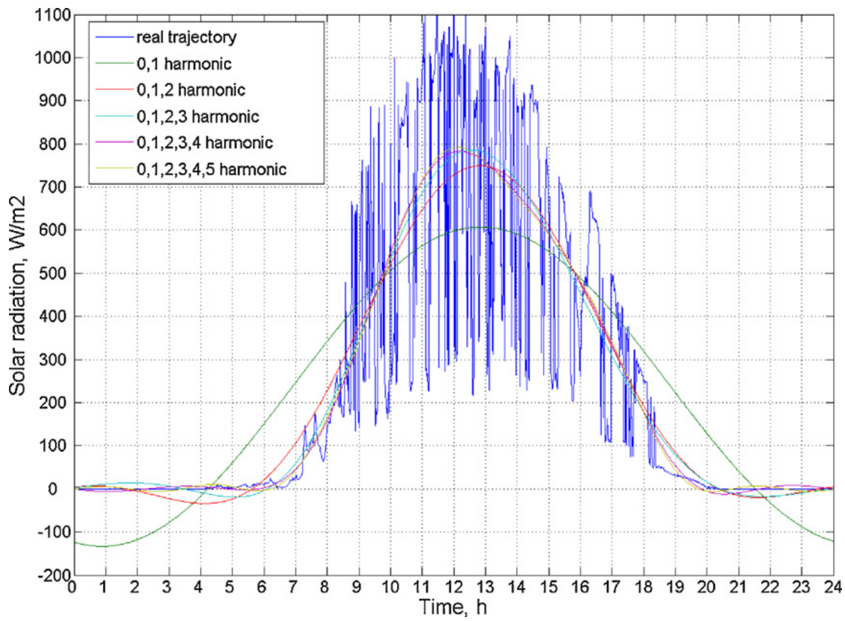

Fig. 1. Selected solar irradiance waveform composed of the constant component and subsequent harmonics on a background of real waveform.

interval duration k should depend on the dynamics of conversion phenomena in a given type of objects. The criterion can be, e.g. thermal time constant. It is determined for collectors according to standard procedures (EN 12975 [20] and ISO 9806 [21]). Obtained thermal time constants depend on collector structure and range from few minutes for flat plate collectors to several minutes for heat pipe tube collector sets. Time constants for heating systems, where the collectors cooperate with heat exchangers and volume tanks of high thermal inertia, amount to tens of minutes. This paper presents daily parameterization of solar irradiation with the use of $(Wz)_d$ index for the most frequently used meteorological data range of 60 min, with introduction of $(Wz)_{d60}$.

The second evaluation method treats solar radiation intensity as a time varied signal $h(\tau)$. Analogically to electric signals, the signal waveform has been analyzed with the use of Fast Fourier Transform (FFT). Harmonic components h_i and their carried power have been determined. The daily radiation spectrum analysis, carried out for several years, shows that main signal power is carried by the constant component h_o (mean value) and the two first harmonics h_1 (of 24-h period) and h_2 (of 12-h period) [22].

Fig. 1 shows the comparison between waveforms composed of the constant and harmonic components for a particular day. It is clear that application of harmonic component higher than the second one causes the signal deformation. The real sun trajectory in relation to measurement surface is represented by the waveform consisted of the constant component and the two first harmonics. The higher harmonics can be regarded as interference in the signal waveform spectrum $h(\tau)$.

That is why, analogically as in electronics, the index THD (*Total Harmonic Distortion*) has been established for the share of harmonics that are qualified as interference in the full signal spectrum:

$$THD = \frac{\sqrt{{h_3}^2 + {h_4}^2 + {h_5}^2 + \cdots + {h_k}^2}}{\sqrt{h_0 + {h_1}^2 + {h_2}^2 + {h_3}^2 + {h_4}^2 + \cdots + {h_k}^2}} \tag{4}$$

where h_0 constant component value, and h_i amplitudes of subsequent harmonics.

It follows from frequency analysis of the $h(\tau)$ signal that amplitude values of particular harmonics depend on cloud cover levels, and their percentage share in the spectrum depends on frequency of cloud cover changes. At higher cloud cover the number of

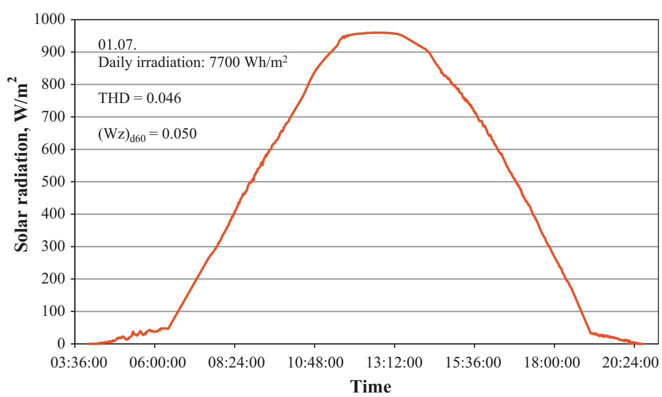

Fig. 2. Deterministic solar irradiance waveform of the tested surface.

harmonic components increases, but the values of main component amplitudes decrease.

The method for daily solar irradiance parameterization by means of THD index does not directly take into account the variation weight in the hours of highest doses, contrary to the method with $(Wz)_d$ index.

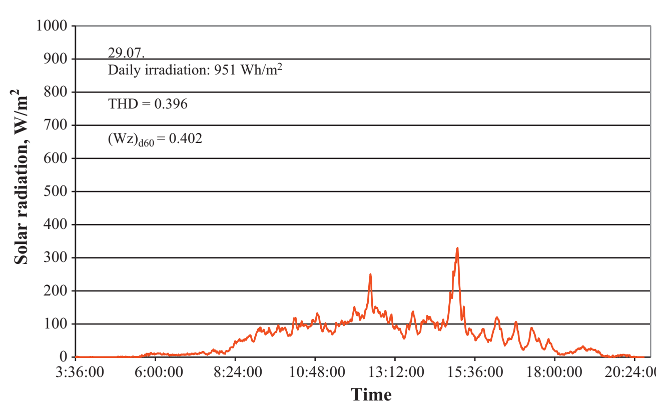

Fig. 3. Solar irradiance variation on a day of full cloud cover.

4. Exemplary results

The irradiance waveform database used for testing of the described parameterization methods includes several hundred days. The measurement surface is south oriented and tilted at 35°. During sunny days (clear sky) the variation index of solar irradiance results from deterministic position of the sun. Fig. 2 shows solar irradiance waveform (for official time) during a clear sky day of high atmosphere visibility. The variation indices are then equal to $(Wz)_{d60} = 0.046$, and THD = 0.050.

Under conditions of almost full cloud cover, when periodical global radiation results from diffuse radiation, irradiance variation is also observed (Fig. 3). The absolute variation range is small then, but relative variations are substantial and thus the indexes THD and $(Wz)_{d60}$ reach values several times higher than that at deterministic radiation variation. The evaluation of irradiance waveforms during days of continuous overcast has only methodical meaning because solar heating systems are not active then.

The subsequent graph (Fig. 4) shows the solar irradiance waveform on a day of several cloud cover phases. Until 11:15 the clouds did not cover the sun, but irradiance changed quickly and in a wide range in two subsequent hours. There was no beam radiation between 13:30 and 15:15 on the measurement surface. Then, until the end of the day, overcast varied. The parameters then were computed as THD = 0.510, and $(Wz)_{d60} = 0.476$.

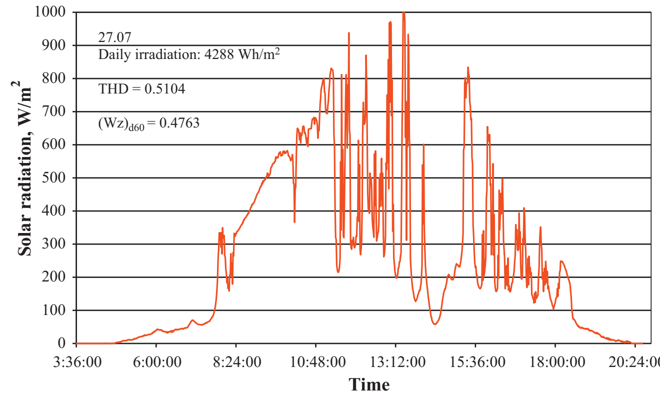

Fig. 4. Solar irradiance variation on a day of varied overcast.

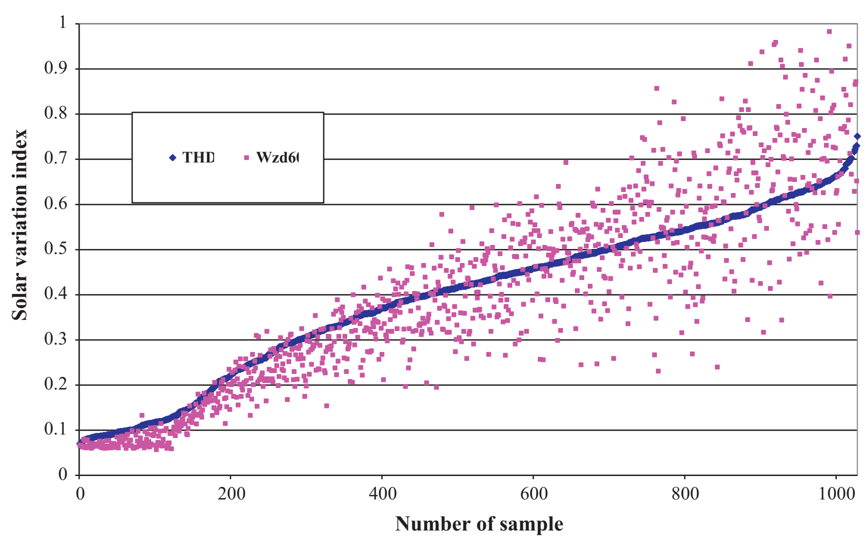

Fig. 5. The comparison of daily indices of solar irradiance variations: THD and $(Wz)_{d60}$.

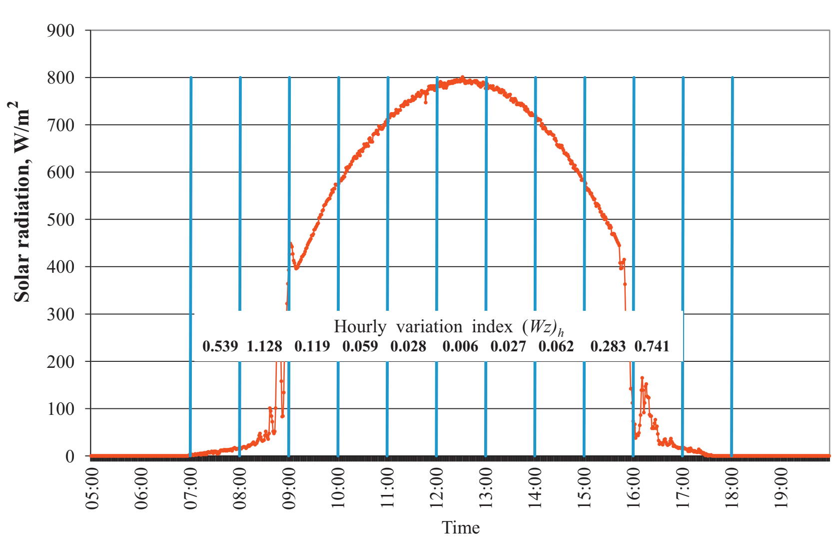

Fig. 6. Solar irradiance conditions parameterized differently by indexes THD and $(Wz)_{d60}$.

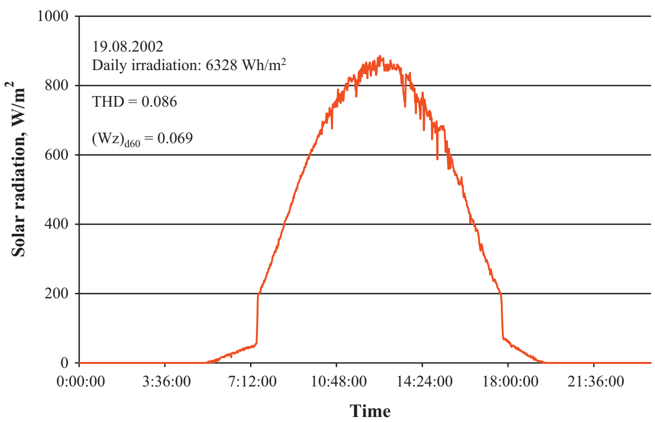

Fig. 7. The variation of test surface irradiance on 19.08.2002.

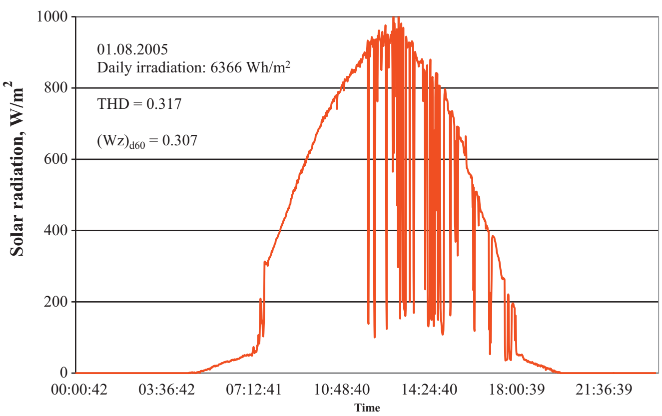

Fig. 8. The variation of test surface irradiance on 01.08.2005.

The best convergence of proposed indexes occurs in the case when for $(Wz)_d$, interval $\Delta\tau = 60$ min. Fig. 5 presents the comparison of both indices for over 1000 days of the period between 80 days before and 80 days after the summer solstice (i.e. between 1st Apr. and 10th Sept.). During the remaining periods of year the test stand is shaded and, thus, the comparison results are not reliable. It has been found that at THD values less than 0.3, the index $(Wz)_{d60}$ is on

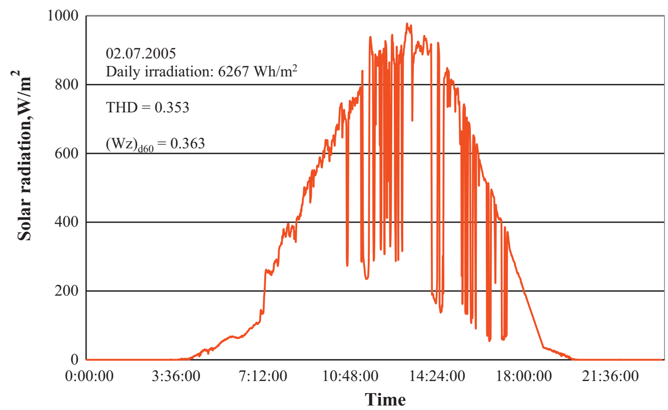

Fig. 9. The variation of test surface irradiance on 02.07.2005.

the average by 18.6% lower in the relative scale, at difference standard deviation of 14.1%. Within the THD range between 0.3 and 0.7, the index $(Wz)_{d60}$ is on the average higher by 0.3%, but difference standard deviation amounts to 20.8%.

In some special conditions of solar irradiance waveform, distinct differences can be observed on the test surface. Such example is a generally clear day, when radiation was limited by fog during morning and evening hours (Fig. 6). The hourly indexes $(Wz)_h$ changed in the wide range from 1.128 at 9 o'clock to 0.006 at 13 o'clock. The arithmetic mean of hourly indexes amounted to 0.3, but the daily index $(Wz)_{d60}$, calculated with the use of particular hours' rank, was reduced to 0.066. The irradiance waveform variation parameterized by THD index was equal to 0.245. That was the case, when both indexes differed distinctly. In such unusual atmospheric conditions the index $(Wz)_{d60}$ better characterized irradiance variation in the context of solar energy use in thermal processes.

The subsequent graphs (Figs. 7–9) indicate that basing on daily global irradiation one cannot conclude on irradiance waveforms during a day. Three exemplary days have been selected from the database (19th Aug., 1st Aug., 2nd Jul.), of almost identical global sum equal to: 6328 Wh/m^2, 6366 Wh/m^2 and 6267 Wh/m^2, respectively. However, variation parameterization showed distinct differences for those days: on the first (clear) day $(Wz)_{d60} = 0.069$ and THD = 0.086, on the second day 0.307 and 0.317, and on the third day 0.363 and 0.353, respectively.

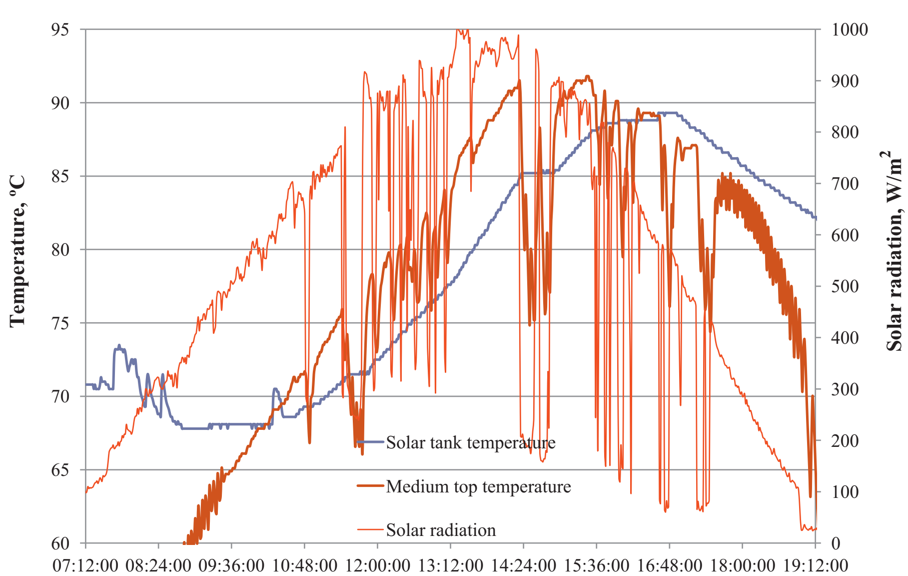

Fig. 10. The waveform of tank heating with battery of collectors on a background of solar irradiance on tested surface on 02.07.2005.

The substantial difference in solar radiation waveforms on the compared days (Figs. 7–9) resulted in exploitation effects of exemplary solar heating system, consisted of tubular heat pipe collectors and a volume heat exchanger [23]. These days provided similar water initial temperature in the accumulation tank, while water disposal during solar system activity was small and almost identical. On 2nd Jul. between 10:00 and 16:00, 11 pauses of medium flow were observed (lasting together 22 min), while the circulation pump medium flow amounted to 2085 dm^3. On 1st Aug. between 10:00 and 16:00, 12 pauses were observed (lasting together 16 min), while the circulation pump medium flow was equal to 2140 dm^3. On 19th Aug. the circulation pump was working continuously and its flow was equal to 2315 dm^3. As a result, the daily efficiency of collectors amounted to 28.6% on the first day, 31.5% on the second day, and 38.5% on the third day. Moreover, it should be mentioned that vacuum collector section of the investigated system works at high temperature in the accumulation tank.

The variability of solar irradiance, particularly in the middle part of the day, influences the waveform of tank heating by the set of collectors. Fig. 10 presents the process of medium heating up in the battery of vacuum collectors and of hot water in the tank on the day characterized by high variation indices. Solar irradiance varied very much between 11:20 and 13:05 and then between 14:20 and 14:50 as well as from 15:30 to 16:00. In the first interference period, the dynamics of heating slowed down and stopped in the second period. The highest temperature increase occurred between 13:05 and 14:20, i.e. in the period of directly visible sun's disk and the increased radiation intensity due to reflection from clouds. However, the final solar irradiation conversion efficiency computed for the whole day was low.

5. Conclusions

In simulations of solar heating and photovoltaic systems the standard averages of hourly radiation data are used. The more professional simulations require short-term data (even 1-min data); this is particularly important in control system problems. Operational tests of real objects aimed at verification of design calculations and comparisons between solar system solutions. The successful completion of these tests calls for precise determination of experimental conditions. The global irradiation data are not precise enough and without additional parameterization of variation are of a limited practical value.

The parameterization of daily solar irradiance variation can be performed with the use of classic indexes: mathematical THD and statistical one (based on the concept of standard deviation). The concepts of both indices have different methodological backgrounds but provide similar results, when a basic range in the statistical method amounts to 60 min. Clear days of solar irradiance deterministic variation are parameterized on the tested surface by indexes of the following values: THD from 0.05 to 0.08 and $(Wz)_{d60}$ between 0.05 and 0.07. The increasing index values point out at higher and higher share of stochastic interference. The advantage of THD index is its standardization that limits its values within the $\langle 0.1 \rangle$ range. The $(Wz)_{d60}$ index value can be higher than 1, but it takes into account higher irradiance values in the better way (through the introduction of weight parameter), which is particularly advantageous for solar heating systems.

Days of similar global irradiation can be characterized by different variations of irradiance in subsequent hours and that is why the introduction of THD or $(Wz)_{d60}$ provides good effects for the purpose of identification. The problem of selection between the proposed indices requires further research.

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